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TECHNICAL REPORT

MATERIAL LABORATORY
NEW YORK NAVAL SHIPYARD
BROOKLYN 1, NEW YORK

SHD-NYNS-900-P-1A

RESEARCH REPORT
ON
A REVIEW OF THE DEVELOPMENT OF A
PLASTIC PHYSICAL SKIN SIMULANT
FOR EVALUATING SUB-FABRIC FLASH BURNS

Lab. Project 5046-3, Part 84
Final Report
NS 081-001

22 July 1955

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Technical Objective AW-7
AFSWP-850

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Lab. Project 5046-3, Part 84
Final Report

SUMMARY

The Naval Material Laboratory has been engaged in the development of a physical skin simulant for evaluating flash burns behind fabric systems. Progress in this development as of 15 May 1955 is summarized in this report.

Prosecution of this project has included study in the following areas:

a. Measurement of some thermal and optical constants of skin, and computation of the skin temperatures associated with burns;

b. development of a thin-film coating to use with the black polyethylene or other skin simulant to approximate the constants of skin;

c. use of the coated polyethylene skin simulant to predict burn severities as compared to porcine skin when covered with various fabric systems;

d. development of the so-called ideal skin simulant having the thermal and optical characteristics of human skin;

e. feasibility of using passive indicators with a physical skin simulant.

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ADMINISTRATIVE INFORMATION

1. The research reported herein was conducted as part of the program originally proposed by COMNAVSHIPYDNYK conf ltr S99/L5, Ser 960-92, of 15 March 1950 and formally approved by Bureau of Ships Restricted Speedletter S99-(O)(348), Ser 348-75, of 6 April 1950. The General Thermal Radiation program at the Naval Material Laboratory is sponsored by the Armed Forces Special Weapons Project.

2. This report covers essentially the material presented by the Naval Material Laboratory on 19 May 1955 at the 14th meeting of the Armed Forces Special Weapons Project Panel on Thermal Radiation and has been prepared in response to several requests for copies of the presentation. For detailed information, reference should be made to the more complete Laboratory project reports.

3. The research reported herein represents the combined efforts of several personnel, including R. Maggio, T. D. Murtha, A. Hirschman, T. B. Gilhooley, and L. Banet, whose services are gratefully acknowledged.

INTRODUCTION

4. The purpose of developing a skin simulant is the study of flash burns behind fabrics in a physical laboratory and use in large-scale field tests where the use of animals might be undesirable from either an operational or statistical viewpoint. The basic requirements for a physical substitute for skin in studying sub-fabric burns are that its thermal and optical properties be comparable to those of average human skin and also that it be durable and easily manipulated. The question naturally arises as to how closely the properties of skin should be matched, since, obviously, a perfect match to all the properties of skin is impossible, and probably not necessary. Since tissue damage is related to the rise in temperature of the skin, it may be said that the physical properties of the skin simulant should approximate those of skin sufficiently so that the heat transfer mechanism and the influence of the backing on the cloth's reaction to radiation, including steaming, charring, ignition and formation of volatile products, be the same for the skin substitute as for skin.

NML SKIN SIMULANT PROGRAM

5. The work carried on during the past year in the NML skin simulant studies may be grouped into five areas. First, the develop-

ment of a coating to use with the polyethylene for a better approximation to the optical constants of skin, and the use of this modified polyethylene skin simulant to predict burns in the pig for comparable exposures. Second, determination of the thermal and optical constants of skin and polyethylene under conditions encountered in the sub-fabric burns, and, using these values, computation of the skin temperatures associated with burns. Third, use of the polyethylene skin simulant in studies of the protection afforded by special fabrics. Fourth, feasibility studies of the use of passive indicators with plastic skin simulants. Fifth, the development of a plastic skin simulant with the thermal and optical constants of skin.

POLYETHYLENE SKIN SIMULANT

6. In the early phases of the skin simulant development, little was known as to the exact values of skin's thermal constants (k c was quoted from 5 to 35X10^{-4} c.g.s. units). The heat transfer mechanism, temperatures and radiant exposures involved in sub-fabric flash burns were not understood. Polyethylene had the highest k c of those substances which could be readily adapted to use as a skin simulant. Polyethylene was chosen for study of the quantitative nature of the factors involved in the sub-fabric burn, having in mind that when the skin constants became more definitely known or when some factor would arise indicating that polyethylene is inadequate to predict burns, a better substance would be employed.

7. The polyethylene skin simulant was employed for the study of the phenomenology associated with burns. At that time (June 1952) arrangements were made with the University of Rochester to obtain pig burn data under standardized conditions. The first factor studied was the thermocouple placement, the only requirement at that time was that its temperature rise be the same under identical exposure conditions. A #30 iron-constantan thermocouple was embedded in the surface. The temperature indicated, however, is not that of the surface, but that of the polyethylene at a depth of 0.023 cm. At this point the control necessary on degree of contact pressure and on spacing tolerance between cloth and backing was determined. The effects of pressure and spacing were studied as well as exposure area, rate of energy delivery and fabric moisture content. From the pig burn data a family of polyethylene temperature histories associated with the various burn levels was determined. These studies allowed the selection of representative and reproducible flash burn situations from the pig burn data that was soon available. This family is described

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and discussed in the NML report on the polyethylene skin simu-
lant. As shown in Fig. 1, the temperature histories associated
with a 2+ burn range from a sharp temperature rise as high as
100°C of relatively short duration to 50°C or lower, maintained
for several seconds. Figure 1 refers to the bare pig, uncovered
polethylene situation, whereas Figures 2, 3, 4 depict the clothed-
pig, covered-polyethylene situation. These figures demonstrate
the similarity of the several temperature histories for diverse
exposure situations.

THEORETICAL CONSIDERATIONS

8. Figures 5 through 8 depict several mathematical analogs of
interest in the skin simulant study. Figure 5 represents the
opaque semi-infinite solid which is applicable to a blackened
substance; Fig. 6 represents the opaque finite medium which
approximates the situation of an irradiated cloth. Figures 7
and 8 represent, respectively, the diathermous semi-infinite
medium and an opaque medium over an opaque semi-infinite medium.
The equations given in these figures must be used with care
in computing the temperatures associated with burns since many
of the important constants are inadequately known for the flash-
burn situation. It is also to be noted that all substances are
diathermous to a degree and that the opaque-solid solution is
always an approximation.

9. Firm thermal contact between an irradiated fabric assembly
and a backing is not always easy to achieve experimentally.
The University of Rochester "contact" or "zero separation"
situation used in sub-fabric burn studies has been shown to
produce temperatures 25 per cent lower than those obtained
for firm contact achieved by applying tension to the cloth.
The effect of pig stubble on the "contact" situation temper-
atures is difficult to compute.

10. The usefulness of theory is unquestioned in obtaining con-
stants from experimental results and in determining approximate
temperature values and the relative effect of the various para-
meters.

COATED POLYETHYLENE SKIN SIMULANT

11. A coating was developed to compensate for the differences in
absorptance and in diathermancy between skin and black polyethy-
lene.[2] The coating is a white Saran paint with titanium oxide
pigment. It is sufficiently thin (0.005 cm) to be thermally in-
significant when used in sub-fabric burn studies. As shown in
Figure 9, the spectral reflectance of the coating is similar to

that of skin so that the modified polyethylene could be used, if
desired, to evaluate burns for most of the sources employed in
these studies.

PREDICTION OF SKIN BURNS

12. The method employed to interpret the temperature histories
of the polyethylene skin simulant in terms of the corresponding
burns to pigs has been empirical; namely, exposing the skin
simulant to situations known to result in a particular burn
severity to pig skin, and using the resulting temperature his-
tory as a criterion. This method is elaborated in the NML
polyethylene report;[1] typical critical temperature histories
are given in Figures 2, 3 and 4. The usefulness of the method
was demonstrated at NML in a study of the so-called Gray series.
Burns behind a set of gray cotton sateens with different absorp-
tances had been evaluated at Rochester. The same cloths were
exposed at NML without reference to the Rochester results. The
temperature histories of the polyethylene skin simulant were de-
termined for various irradiances and times of exposure. From
the temperature histories obtained and from the corresponding
"critical" temperature histories known from the previous
studies to result in pig burns, it was possible to determine
which temperature histories would result in pig burns. It was
then possible to assign a critical radiant exposure for each
time of exposure. These data are shown in Table 1. Data are
included for both zero and 5 mm spacing, for low and high irrad-
iances, for opaque and transmitting cloths. The agreement be-
tween the two sets of data is very good for the 5-mm spacing
situation. The data for zero separation do not correlate as
well, probably due to the difficulties encountered in obtaining
a contact burn in the pig because of his stubble. In this ex-
periment it was noted that differences in air supply and in
depth of aperture may cause differences in temperature histories
as large as 100 per cent. This experiment parallels that at
Rochester,[3] except for the significant facts that the absorp-
tance of the skin simulant was modified and that burns are pre-
dicted on the basis of temperature history rather than tempera-
ture maximum. The transmission of the fabrics varies from
15 per cent for the white to zero for the darker shades; the
use of the Saran paint film over the black polyethylene re-
sulted in differences in predicting the radiant exposure for
2+ burns as large as 30 per cent for the situation in which
the cloth is in contact with the backing and as large 100 per
cent for the situation in which the cloth and backing are
separated by air.

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OPTICAL CONSTANTS OF SKIN

13. The spectral reflectance of human skin was determined for four subjects with the NML Recording Reflectometer.[4,5] The spectral absorptance, which is defined as "one minus the reflectance", is shown in Figure 10, together with the spectra of three sources which are of interest in the skin simulant studies. The curve is the average for four areas (forearm, back of arm, palm, and forehead) of four individuals, a fair Caucasian, a ruddy Caucasian, and two medium Negroes. The average total absorptance for carbon-arc radiation, for all four areas for all four individuals is 0.72, within $\pm$ 5 per cent. There was no appreciable difference in this value for 3000°K and 6000°K Planckian radiation.

THERMAL CONSTANTS OF SKIN, SKIN TEMPERATURES

14. The surface temperatures of several individuals were measured upon exposure to intense thermal radiation at levels equal to or below that corresponding to pain in the subject.[6] From the measurements on blackened skin, k c was determined to be 8.6×10^{-4}, which value holds for exposures from 20 seconds down to 0.2 second. This value corresponds closely to that [7] of Hardy, 9×10^{-4}, which was obtained for longer exposures than those used in the NML studies. The primary objective of this experiment, the validity of this method for determining the k c of skin simulant plastics, was considered to have been established.

15. The temperatures of unmodified human skin for carbon-arc irradiation are shown in Figure 11. It is to be noted that for exposures longer than 1 second the surface temperatures may be approximated by opaque-solid theory and an artificial absorptance of 0.5, and more realistically from a physical viewpoint by diathermous-solid theory, using the spectrophotometrically determined absorptance of 0.72 and a of 30 per cm. The best fit over the entire range of times investigated is given by assuming that the incident carbon-arc radiation has two components, one with an extinction coefficient of 5 per cm over the spectral region from 0.55 to 1.35 microns in which 28 per cent of the total incident radiation is absorbed, and the other, opaque ($=\infty$) for ultraviolet and visible radiation below 0.55 micron and for infrared radiation beyond 1.35 microns, in which regions 44 per cent of the total incident energy is absorbed.

16. In order to check and extend the temperature criteria which
have been determined empirically and in order to evaluate other
criteria for predicting burn severities, the temperatures of skin
for situations resulting in burns have been computed, using the
thermal and optical constants as determined at NML. First,
using opaque solid theory and the artificial absorptance, the maxi-
mum temperature rise was determined as a function of exposure time
for several depths up to 2 mm, and for exposures which will cause a
2+ burn in pig skin. The data are presented in two forms in Figures
12 and 13. The general pattern one would expect is shown here,
where for short times, contrasted to the longer exposure times, 2+
mild burns involve high temperature rises at the surface and low
temperature rises at the greater depths. The temperature-depth
profile in Figure 13 shows the approximate depth of heat penetration
for various exposures and a depth (0.05 cm) at which the maximum
temperature rise, on the basis of these assumptions, is independent
of the time of exposure.

17. The more realistic, but more complex, computation involves the
use of an absorptance which varies with the exposure time to com-
pensate for the diathermancy value which must be used in order
to explain the temperatures of the surface as measured. Using
opaque solid theory, the temperature-depth-time profiles have
been determined, as shown in Figures 14 and 15. For the shorter
exposures the temperatures are higher, and at a depth of approx-
imately 0.04 cm the temperature rise is the same for all exposure
times. Computations, using diathermous-solid theory, are incom-
plete, but they should give a more realistic picture.

SELF-RECORDING SKIN SIMULANT

18. Because field use of a self-recording skin simulant would
eliminate complex and costly instrumentation, some attention
has been given to studying the feasibility of such a system.
The best system to date employs temperature-sensitive papers.
The papers are set into the skin simulant perpendicularly to
the surface. The papers do not alter the heat flow in the
skin simulant, since most of the heat flow is parallel to the
plane of the paper. Several papers of different temperature
sensitivities are employed and a temperature maximum versus
depth profile is the measured quantity. The wax on the paper
will melt at the surface of the polyethylene and at all depths
for which the temperature exceeds the critical value of the
paper. Rectangular pulses known to result in various burn
severities were applied to a dark gray cotton sateen behind
which the self-recording polyethylene skin simulant was
mounted with zero separation behind the cloth. The expo-

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sure conditions employed in this series were obtained by considera-
tion of the University of Rochester data on pig burns behind cloth.
With minor modifications, they represent ED_{50} dosages for the 1+
severe and 2+ severe burn levels, respectively, for various expo-
sure times on pigs clothed in the identical manner. In Figures
16, 17, and 18, the temperature indicated by specific papers is
plotted as a function of the depth beneath the surface for which
the temperature exceeded the critical value. Figures 16, 17,
and 18 represent exposures of less than 1 second, approximately
5 seconds, and approximately 10 seconds, respectively. The cri-
tical temperatures for the papers are those assigned for them by
the Quartermaster Corps and by the University of Dayton, and are
believed to be reasonably accurate. Examination of the data given
in these three figures indicates that a 2+ severe burn can be
distinguished readily from a 1+ severe burn, and that the method
has value. Considerable additional work must be done in this
field; NML proposes to continue this work and would welcome any
suggestions which would aid in the further development of a self-
recording skin simulant.

IDEAL SKIN SIMULANT

19. It was feasible to proceed with a skin simulant matching the
thermal and optical constants of skin with the publication of
Hardy's data for $k\rho c$ and with the development of a valid method
of determining thermal constants of plastics from surface tem-
peratures. The criterion for the ideal skin simulant is that its
constants should match the thermal characteristics of skin, i.e.,
$k\rho c = 9 \times 10^{-4}$ and $\rho c = 0.8$. Emphasis is placed on its use as a
sub-fabric burn indicator, for which both $k\rho c$ and $k/\rho c$ are import-
ant, but consideration would also be given to the bare or un-
covered situation. For this reason, the optical match to skin is
considered to be of secondary importance. A synthetic optical
match is readily possible, as demonstrated in the case of polyethy-
lene. A full optical match is also possible.

20. The general program involves the selection of a plastic
having approximately the proper thermal constants and mixing
into it various amounts of an inorganic powder such as copper
or quartz, until a match of the thermal constants of skin is
achieved. Several base plastics have been investigated so that
the one with the best physical properties could be chosen. The
variation of $k\rho c$ with composition for a given molding cycle for
20 gram specimens cast in $1\frac{1}{2}$-inch diameter discs is shown in
Fig. 19. The $k\rho c$ product was determined by surface temperature

measurements with the fine-wire thermocouple. One might conclude that the desired $k\rho c$ is readily achieved, provided the correct ratio of filler powder to resin is employed. These data are based on measurements on the first samples, which were made with a single pressure and temperature molding cycle on a press which had limited application. A new molding press was received in February which allowed a variety of sample sizes and a variable molding cycle which would give better control over air pockets and other molding faults. On the other hand, it was discovered recently that the particular molding cycle may change the $k\rho c$ product for some of the skin simulants and most likely, the simulant's thermal diffusivity ($k/\rho c$). The various mixes which give a $k\rho c$ of approximately 8.6×10^{-4} are tabulated in Table 2, together with the densities which were determined experimentally, the specific heats which were calculated by the method of mixtures from handbook data, and the resulting computed ρc's and $k/\rho c$'s. Again, it should be noted that these data hold for a given molding cycle for 20 - gram specimens cast in $1\frac{1}{2}$-inch diameter discs. It may also be noted that the use of copper powder results in an essentially opaque substance, whereas the use of quartz powder results in an essentially diathermous substance. For this reason, NML at the present time prefers the Beetle-quartz combination.

21. As projected by AFSWP, NML is to prepare a series of skin simulants for distribution to the various laboratories engaged in this field for their evaluation and study. Inasmuch as the handbook values for the constants are not necessarily appropriate when the material is in powder form, and since these constants are affected by the particular molding cycle, NML believes that distribution of the skin simulants should be postponed until reproducible homogeneous units can be prepared, having thermal and optical constants documented by direct experimentation. Calorimetric equipment for measuring specific heats is on order and should be delivered in one or two weeks. Earlier distribution of the skin is possible, but, because of nonuniformity of the material, may lead only to eventual confusion as to the actual merits of the skin simulant.

FUTURE PLANS

22. The immediate task with highest priority at NML is the processing and distribution of the skin simulants. In addition to documenting the thermal constants of the units, NML will perform the following test of adequacy, as agreed at the December meeting at Technical Operations. The skin simulant and human skin will
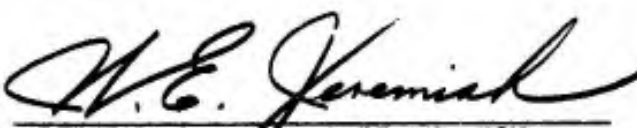
be subjected to identical thermal pulses, when covered with an opaque clothing assembly. Surface temperatures will be measured. If the surface temperature histories for the skin and skin simulant are the same for this and for cloth conditions involving other modes of heat transfer, then the skin simulant is probably adequate. The subsequent phases, in which the other laboratories will cooperate, involve measurements at a depth specified by the skin simulant's constants; if the temperatures are the same for the skin simulant and for porcine and rat skin, then it is safe to conclude that the skin simulant is valid for studying sub-fabric burns.

23. When the validity of the ideal skin simulant is established, a series of temperature histories of the skin simulant will have been obtained for specific exposure situations which result in burns to skin. It will then be necessary to develop a general burn criterion. For this purpose, the reaction rate integral proposed by Henriques may be a suitable empirical tool. Secondly, experiment may bear out the calculations which indicate that at a certain depth the temperature will rise to a maximum value which is the same for all times of exposure. The work at NML in this direction will be pursued, applying diathermous-solid theory to the problem at hand. Thirdly, the characteristics of the temperature histories may be such that a general relationship may be drawn, correlating the temperature histories in the immediate vicinity of the temperature maximum. This possibility will be examined.

24. When these phases of the skin simulant program are completed, NML will then turn its attention to the basic studies of the sub-fabric flash burn. In the interim, in its Laboratory Services Testing Program, NML will employ the polyethylene skin simulant as required to determine the heat transfer characteristics of fabric systems.

Approved:

for A. B. JONES, Jr., CAPTAIN, USN
The Director

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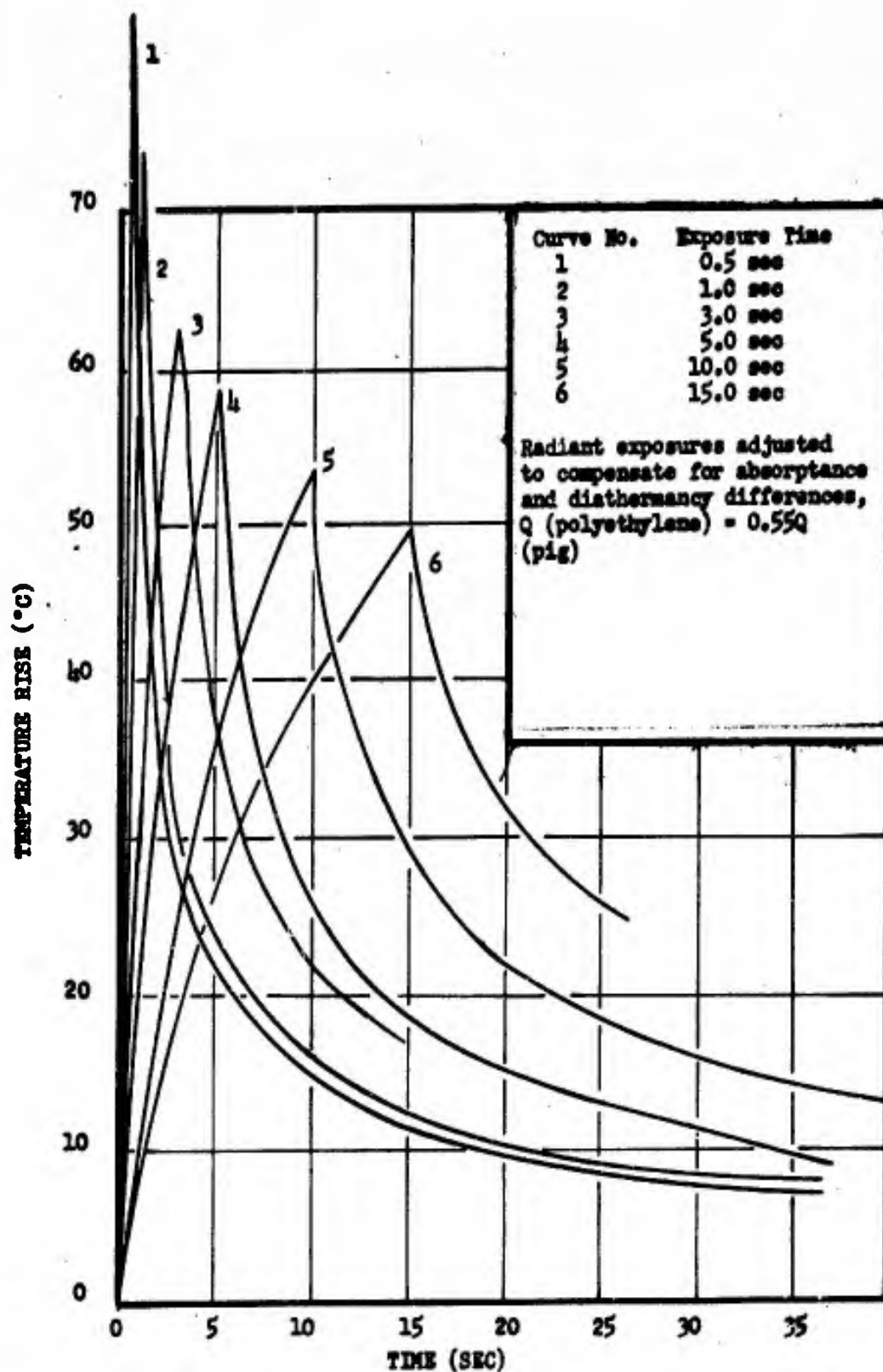
Fig. 1 - Temperature Histories of the Uncovered Black Polyethylene Skin Simulant, Corresponding to a 2+ Mild Burn in Pig Skin, for Several Exposure Times
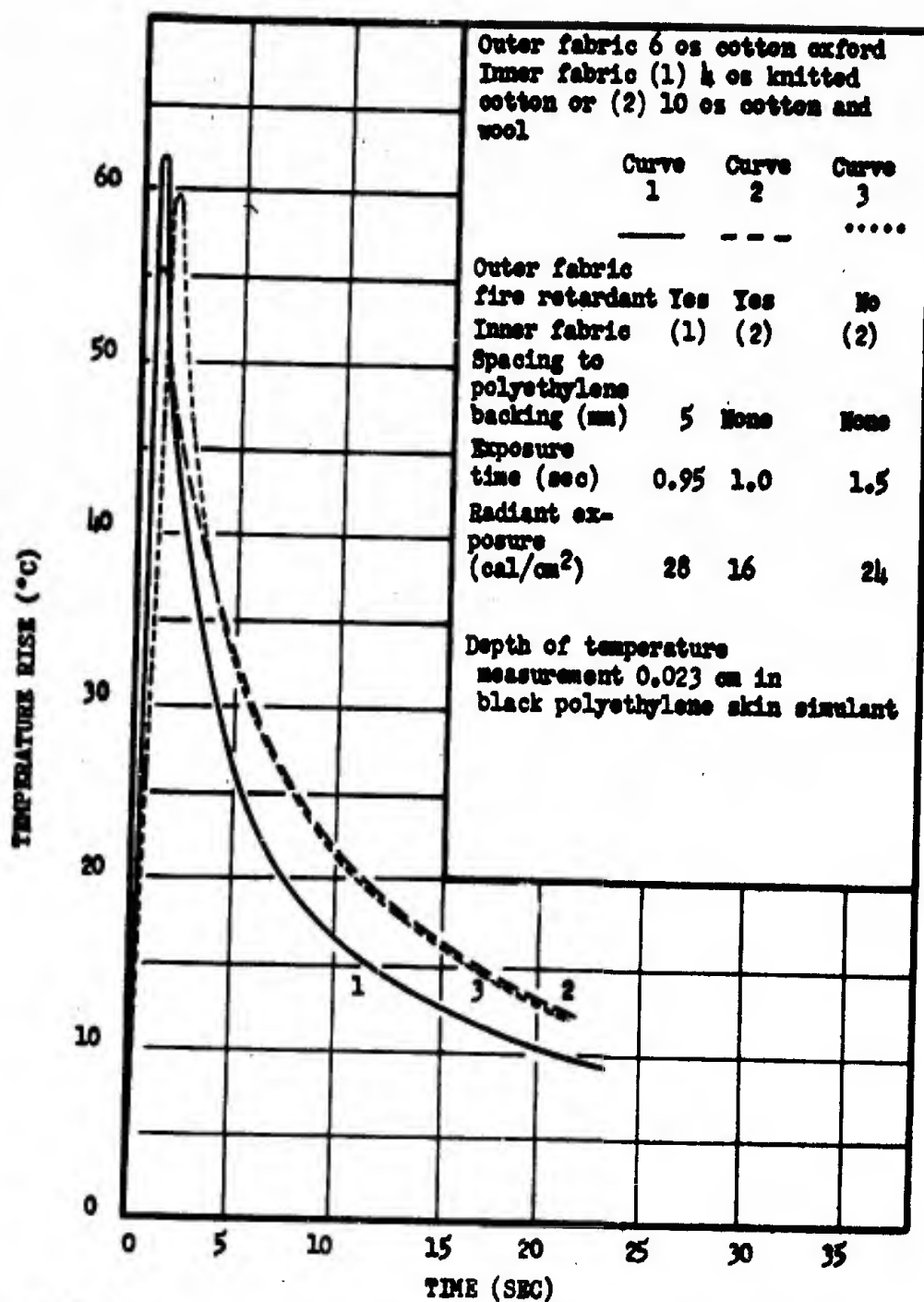
Fig. 2 - Temperature Histories of Covered Polyethylene Corresponding to a 2+ Mild Burn in Pig Skin; Typical Clothing Assemblies
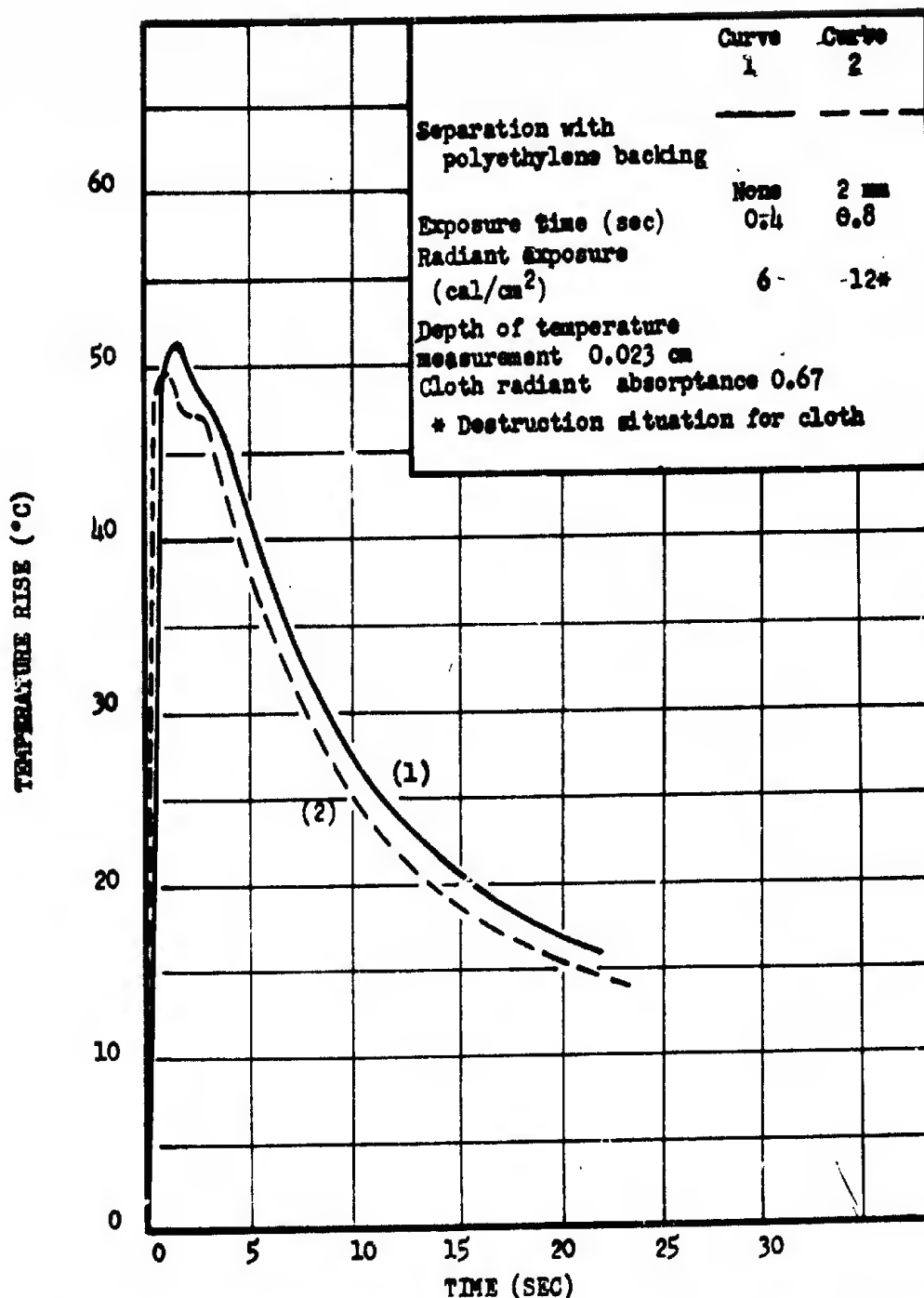
Fig. 3 -   Temperature Histories of Covered Polyethylene
Corresponding to a 2+ Mild Burn in Pig Skin;
Single Layer of OG Cotton Sateen

Exposure time, 6.4 sec
Radiant exposure, 9.5 cal/cm^2
No separation with polyethylene
    or between cloths
Depth of temperature measurement, 0.023 cm
Cloth radiant absorptance, 0.67
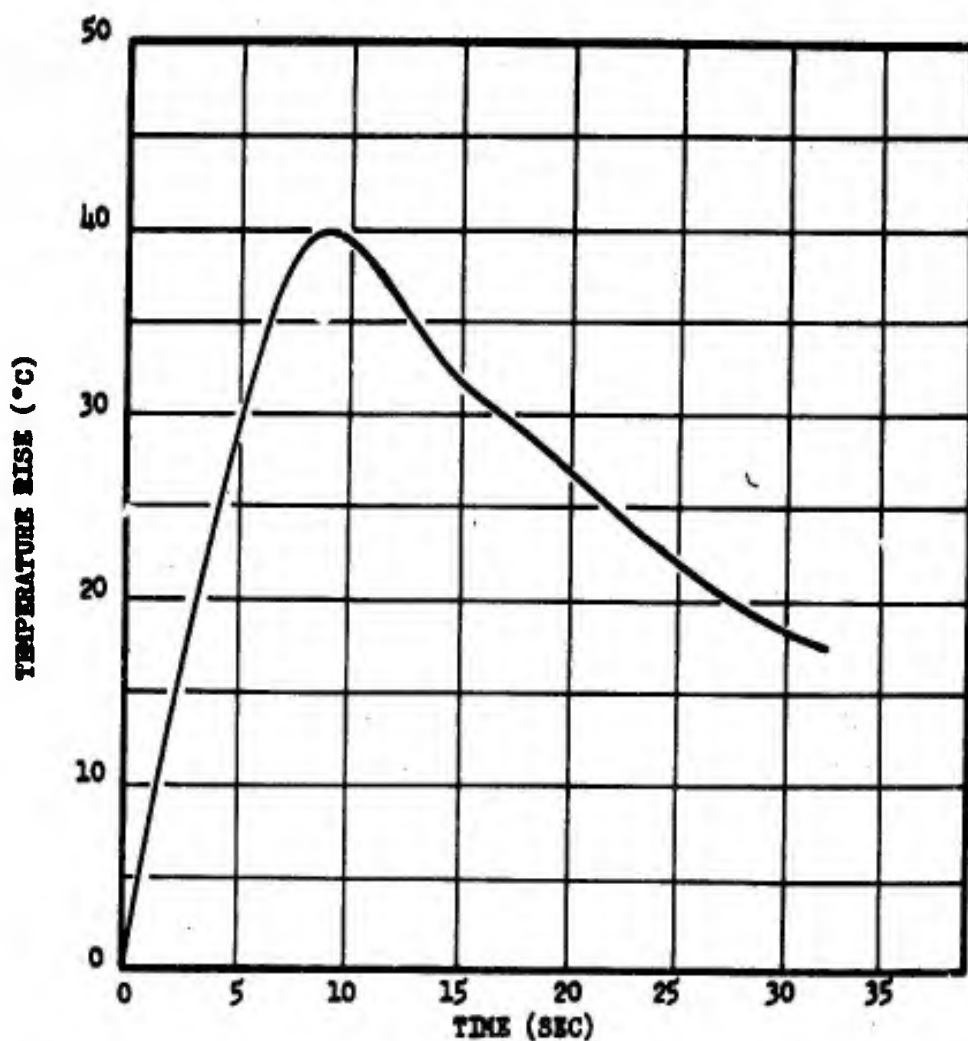
Fig. 4 - Temperature History of Covered Polyethylene
        Corresponding to a 2+ Mild Burn in Pig Skin;
        Two Layers of OG Cotton Sateen
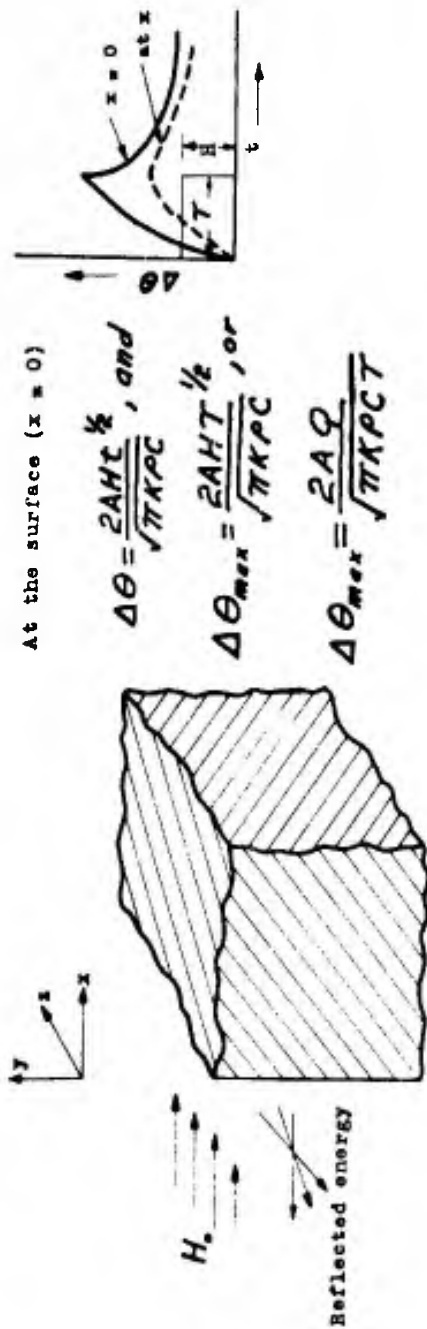
At the surface (x = 0)

$$\Delta\theta = \frac{2AHt^{1/2}}{\sqrt{\pi KPC}}, \text{ and}$$

$$\Delta\theta_{max} = \frac{2AHT^{1/2}}{\sqrt{\pi KPC}}, \text{ or}$$

$$\Delta\theta_{max} = \frac{2AQ}{\sqrt{\pi KPCT}}$$

At depth X

$$\Delta\theta = \frac{2AHt^{1/2}}{\sqrt{\pi KPC}}\left[e^{-x^2/4ht} - \frac{\sqrt{\pi}}{2}\frac{x}{\sqrt{ht}}\ erfc(x/\sqrt{4ht})\right]$$

$$erfc(x/\sqrt{4ht}) = 1 - \frac{2}{\sqrt{\pi}}\int_0^{x/\sqrt{4ht}} e^{-v^2}dv$$

θ Temperature rise (°C)   K   Conductivity (cal/sec cm °C)
A Radiant Absorptance ρ Density (gms/cm³)
H Irradiance (cal/cm²sec)   c   Specific heat (cal/gm °C)
t Time of reference (sec)   h   Thermal diffusivity K/ρc
T Time of exposure (sec)   Q   Radiant Exposure (cal/cm²)

Reradiation and convection losses not included in derivation

Fig. 5 - Semi-Infinite Opaque Solid Representing An Opaque Skin Or Skin Simulant

H.

Reflected
Energy
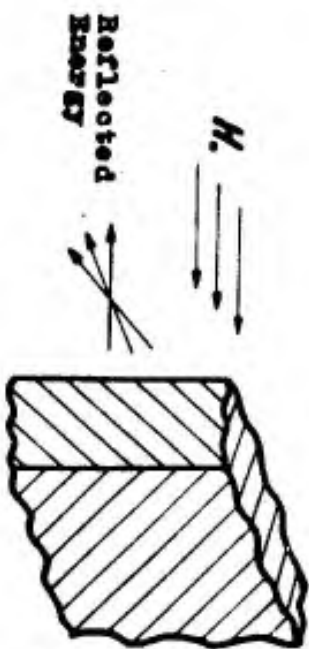
$$\Delta\theta = \frac{2AHt^{1/2}}{\sqrt{\pi k\rho c}}\left[1+2\sum_{n=0}^{\infty} e^{-(2nz)^2} - 2\sqrt{\pi}\, nz\, erfc(2nz)\right]$$

θ Temperature rise (°C)
A Radiant Absorptance
H Irradiance (cal/cm² sec)
t Time of reference (sec)
l Thickness (cm)

k Conductivity (cal/sec cm °C)
ρ Density (gms/cm³)
c Specific heat (cal/gm °C)
h Thermal diffusivity k/ρc

Reradiation and convection losses not included in derivation

Useful for short exposure times and low conductivities as in the case of fabrics

Fig. 6 - Temperature Rise Of The Irradiated Face Of A
Finite Opaque Solid

Temperature rise of diathermous semi-infinite solid

$$\Delta\theta = \frac{(1-R)H}{K}\left\{2\left(\frac{ht}{\pi}\right)^{1/2}e^{-x^2/4ht} - x\,\text{erfc}\left(\frac{x}{\sqrt{4ht}}\right) + \frac{e^{\gamma^2 ht}}{2\gamma}\left[e^{-\gamma x}\,\text{erfc}\left(\gamma\sqrt{ht}-\frac{x}{\sqrt{4ht}}\right) + e^{\gamma x}\,\text{erfc}\left(\gamma\sqrt{ht}+\frac{x}{\sqrt{4ht}}\right)\right] - \frac{e^{-\gamma x}}{\gamma}\right\}$$

Temperature rise at the surface of a diathermous semi-infinite solid

$$\Delta\theta = \frac{(1-R)H}{K}\left\{2\left(\frac{ht}{\pi}\right)^{1/2} + \frac{e^{\gamma^2 ht}}{\gamma}\,\text{erfc}\,\gamma\sqrt{ht} - \frac{1}{\gamma}\right\}$$

$H_x = H_o(1-R)e^{-\gamma x}$

θ Temperature rise (°C)
R   Radiant Reflectance
H   Irradiance (cal/cm² sec)
t   Time of reference (sec)
h Time of exposure (sec)

K   Conductivity (cal/sec cm °C)
ρ Density (gms/cm³)
c   Specific heat (cal/gm °C)
γ Extinction Coefficient (cm⁻¹)

Reradiation and convection losses not included in derivation

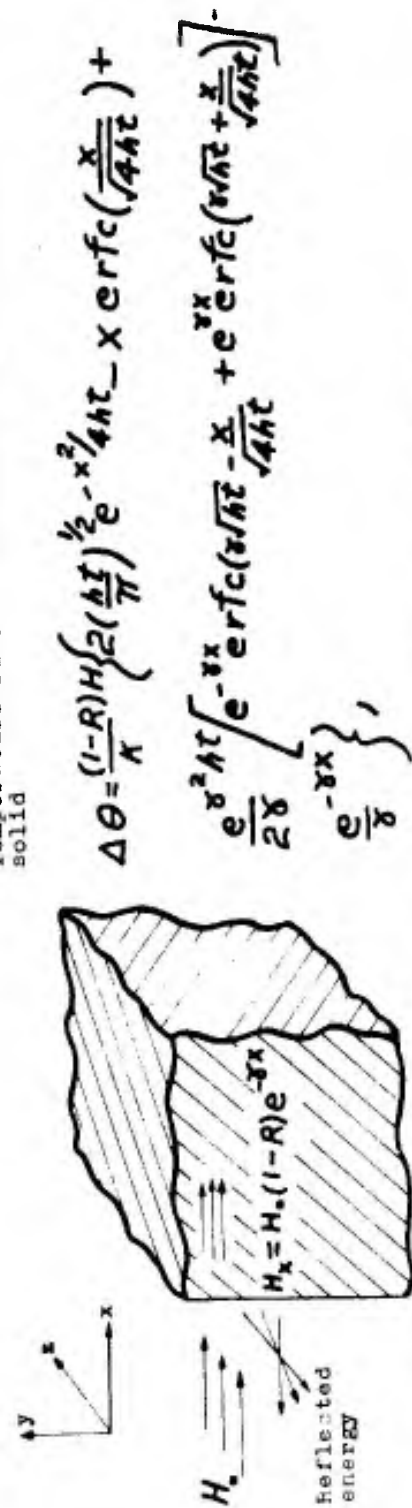Fig. 7 - Semi-Infinite Diathermous Solid Representing Skin Or Skin Simulant Which Absorbs Radiant Energy In Depth
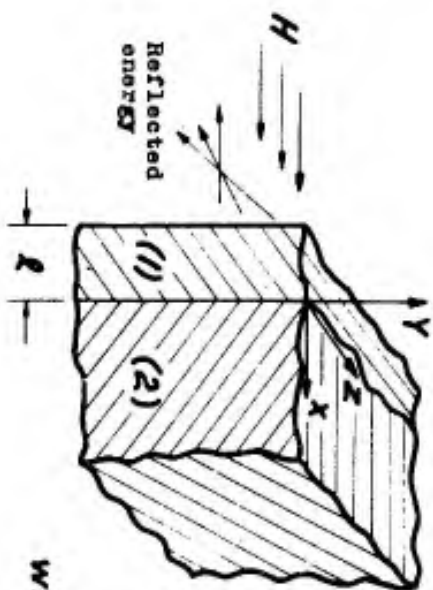
$$\Delta\Theta = \frac{4AHt}{\sqrt{\pi K_1 \rho_1 C_1}} \left(\frac{1}{1+\sigma}\right) \sum_{n=0}^{\infty} a^n \left[e^{-z^2} - \sqrt{\pi}\, z\, erfc\, z\right], \text{ where}$$

$$\sigma = \sqrt{\frac{K_1 \rho_1 C_1}{K_2 \rho_2 C_2}}, \quad a = \frac{1-\sigma}{1+\sigma} \quad \text{and} \quad Z = \frac{(2n+1)\ell}{2\sqrt{h_1 t}}$$

where $X=0$; or $Z = \frac{(2n+1)\ell + x\sqrt{h_1/h_2}}{2\sqrt{h_1 t}}$, at depth X

θ Temperature rise (°C)
A Radiant Absorptance
H Irradiance (cal/cm²sec)
t Time of reference (sec)
h Time of exposure (sec)

K Conductivity (cal/sec cm °C)
ρ Density (gms/cm³)
c Specific heat (cal/gm °C)
ℓ Cloth thickness (cm)

$$erfc\, z = 1 - \frac{2}{\sqrt{\pi}} \int_0^z e^{-v^2} dv$$

Reradiation and convection losses not included in derivation

Fig. 8 - Finite Opaque Medium In Perfect Thermal Contact With A Semi-Infinite Medium, Representing A Cloth-Covered Skin Or Skin Simulant
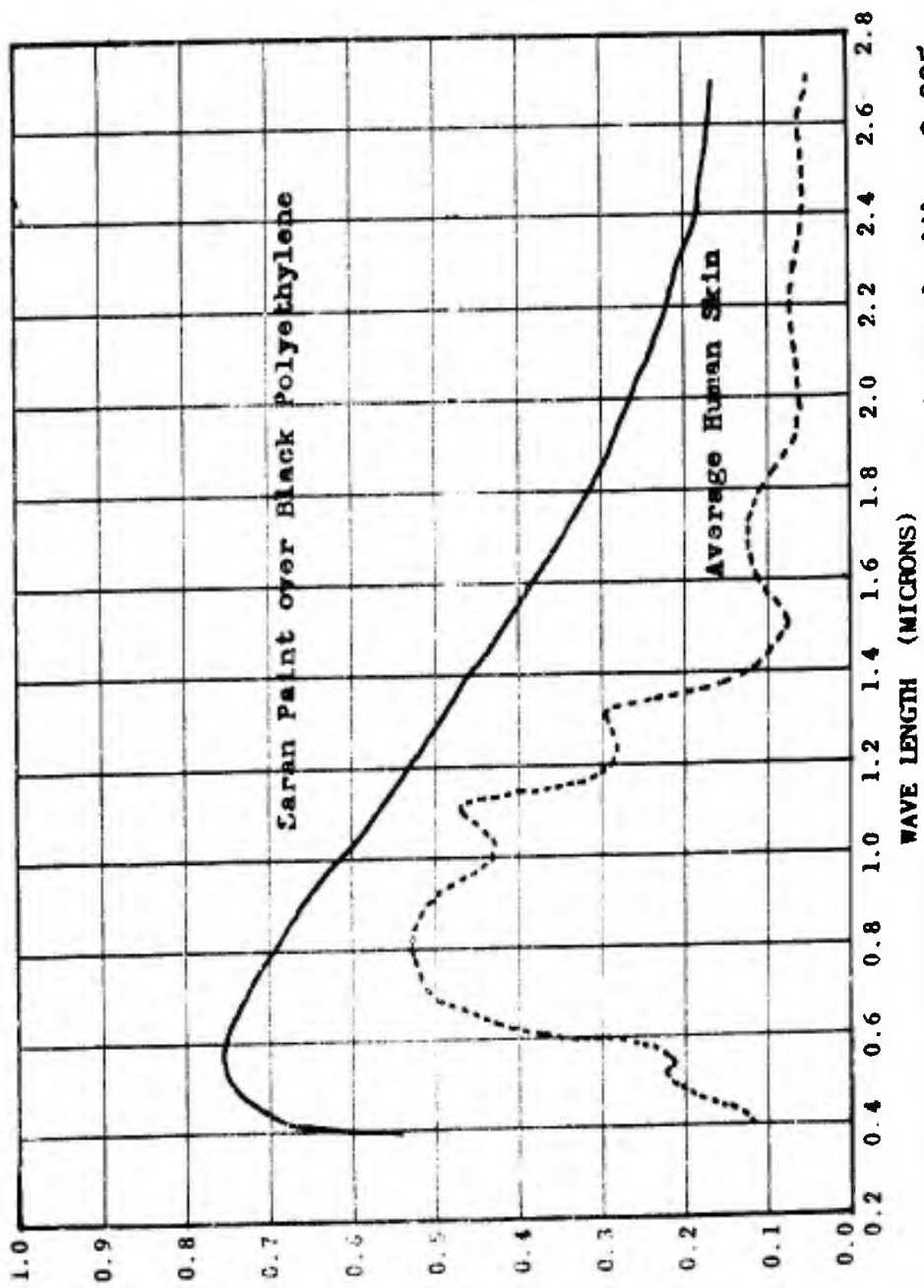
Fig. 9. Reflectance of Black Polyethylene Covered with a 0.005 cm Film of Saran Paint and the Average Reflectance of Human Skin

RELATIVE ENERGY

REFLECTANCE

Carbon Arc

3000° K Black Body
and IR Filter

3000° K Black Body

Skin
Reflectance

WAVE LENGTH (MICRONS)

Fig.10 - Spectral Energy Distribution of Carbon-arc, 3000°K
Planckian Radiation (Unfiltered and Filtered to Pass Only
Infrared Radiation), and the Average Reflectance of Human Skin

Fig. 11 – Experimental and Calculated Human Skin Surface Temperature
Rises for Carbon-arc Radiation

MAXIMUM TEMPERATURE RISE (°C)

EXPOSURE TIME (SEC)

x = 0

0.01cm

0.02

0.05

0.10

0.20

Assumptions:
Skin opaque, A' = 0.5
$k\rho c = 8.6 \times 10^{-4}$
$\rho c = 0.8$
$k/\rho c = 13.5 \times 10^{-4}$
$k = 10.6 \times 10^{-4}$

Fig.12 - Maximum Temperature Rise Computed for Human Skin for Radiant Exposures
Resulting in 2 + Mild Burns in Pig Skin

Fig. 13 - Maximum Temperature Rise Computed for
Human Skin for Radiant Exposures for
2 + Mild Burn in Pig Skin

MAXIMUM TEMPERATURE RISE (°C)

Assumption: Skin is Opaque
$\Delta' = f(\tau)$ Experimental Surface $\Delta\theta/H$
$k\rho c = 8.6x10^{-4}, \rho c = 0.8$

x=0

0.01cm

0.02

0.05

0.10

0.20

EXPOSURE TIME (SEC)
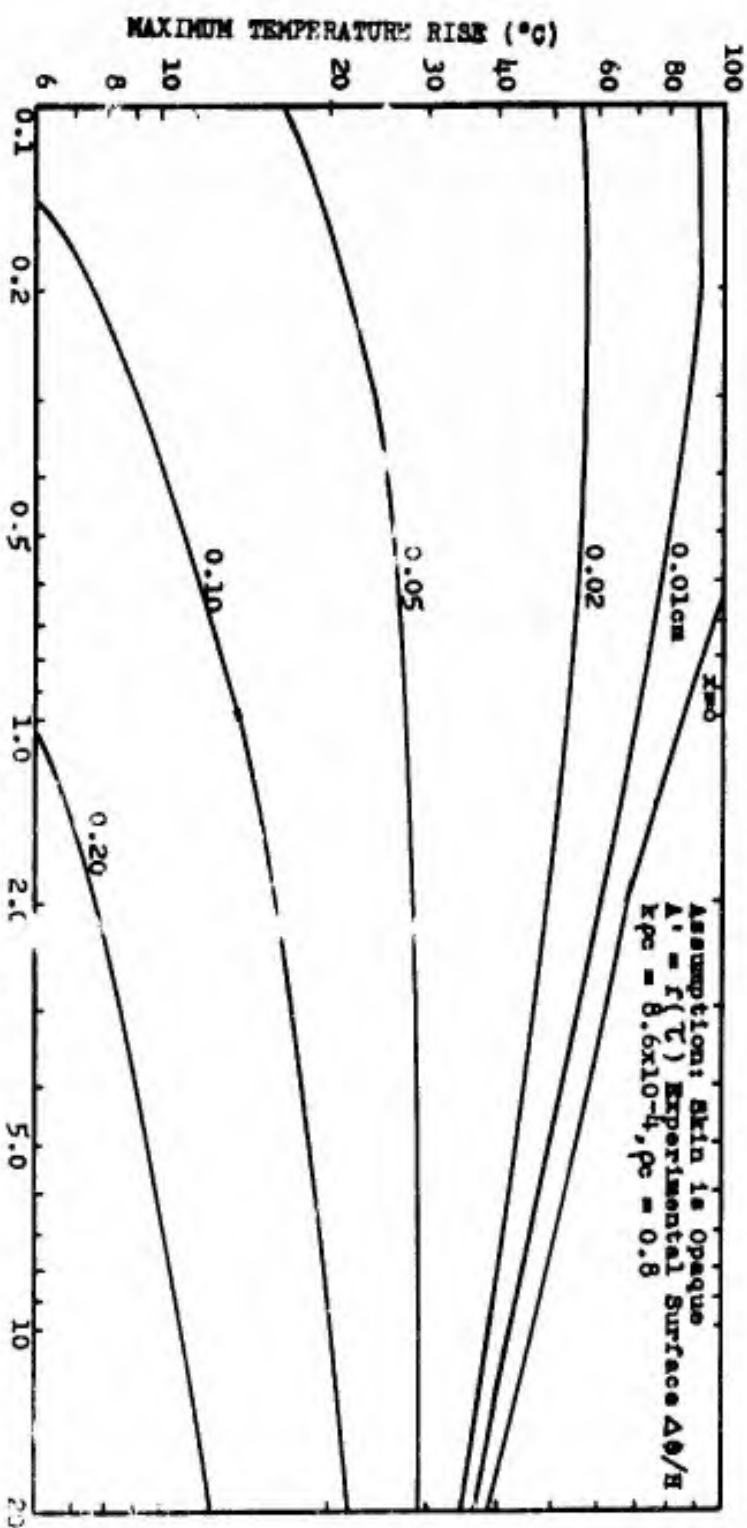
Fig. 14 - Maximum Temperature Rise Computed for Human Skin for Radiant Exposures
Resulting in 2 + Mild Burns in Pig Skin
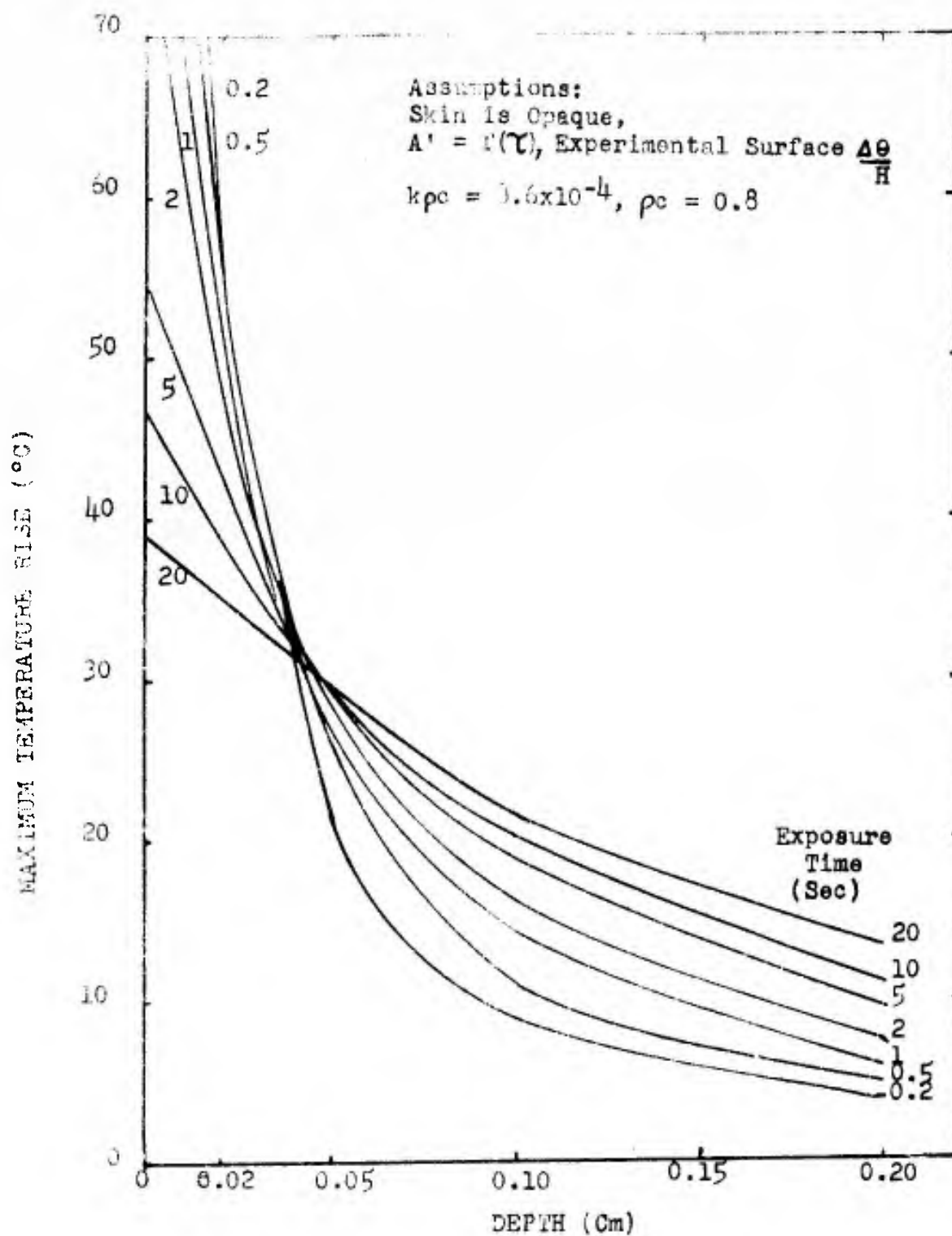
Fig.15 - Maximum Temperature Rise Computed for
Human Skin for Radiant Exposures Re-
sulting in 2 + Mild Burns in Pig Skin

Fig. 16 – Maximum Temperature as a Function of Depth in
Polyethylene as Determined by Four Temperature
Sensitive Papers

x 1+ severe $\begin{cases} H = 1.1 \text{ cal/cm}^2\text{sec} \\ t = 4.0 \text{ sec} \end{cases}$

o 2+ severe $\begin{cases} H = 1.1 \text{ cal/cm}^2\text{sec} \\ t = 6.0 \text{ sec} \end{cases}$

One layer of cotton sateen 9oz,
dark gray, at zero separation

DEPTH (mm)

TEMPERATURE (°C)

Skin Temperature as a Function of Depth in
Skin as Determined by Four Temperature
Sensitive Papers

TEMPERATURE (°C)

52

62

67

72

DEPTH (mm)

0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

x 1+ severe $\left\{\begin{array}{l} H = 0.55 \ cal/cm^2 sec \\ t = 9.0 \ sec \end{array}\right.$

⊝ 2+ severe $\left\{\begin{array}{l} H = 0.72 \ cal/cm^2 sec \\ t = 10.5 \ sec \end{array}\right.$
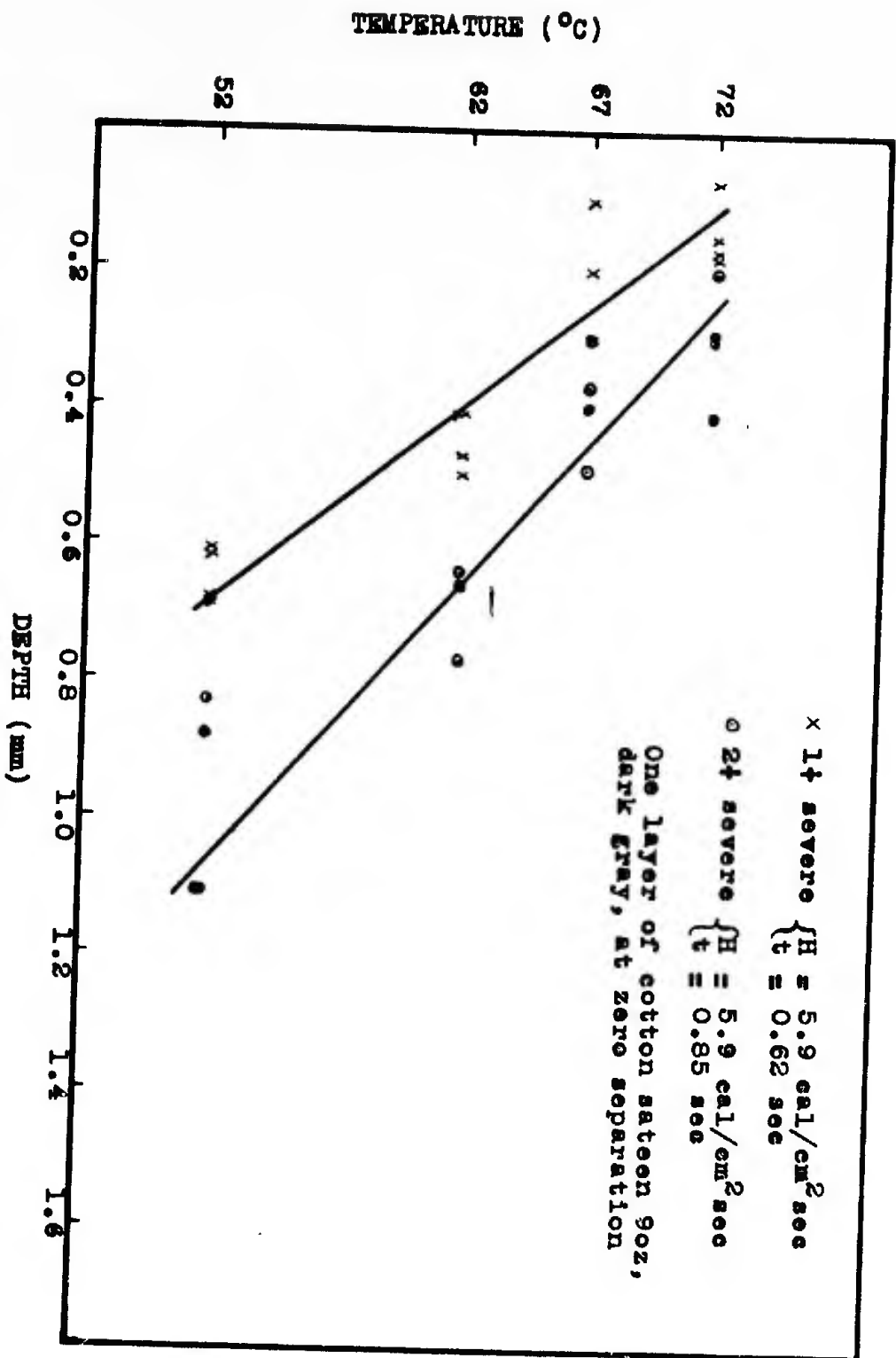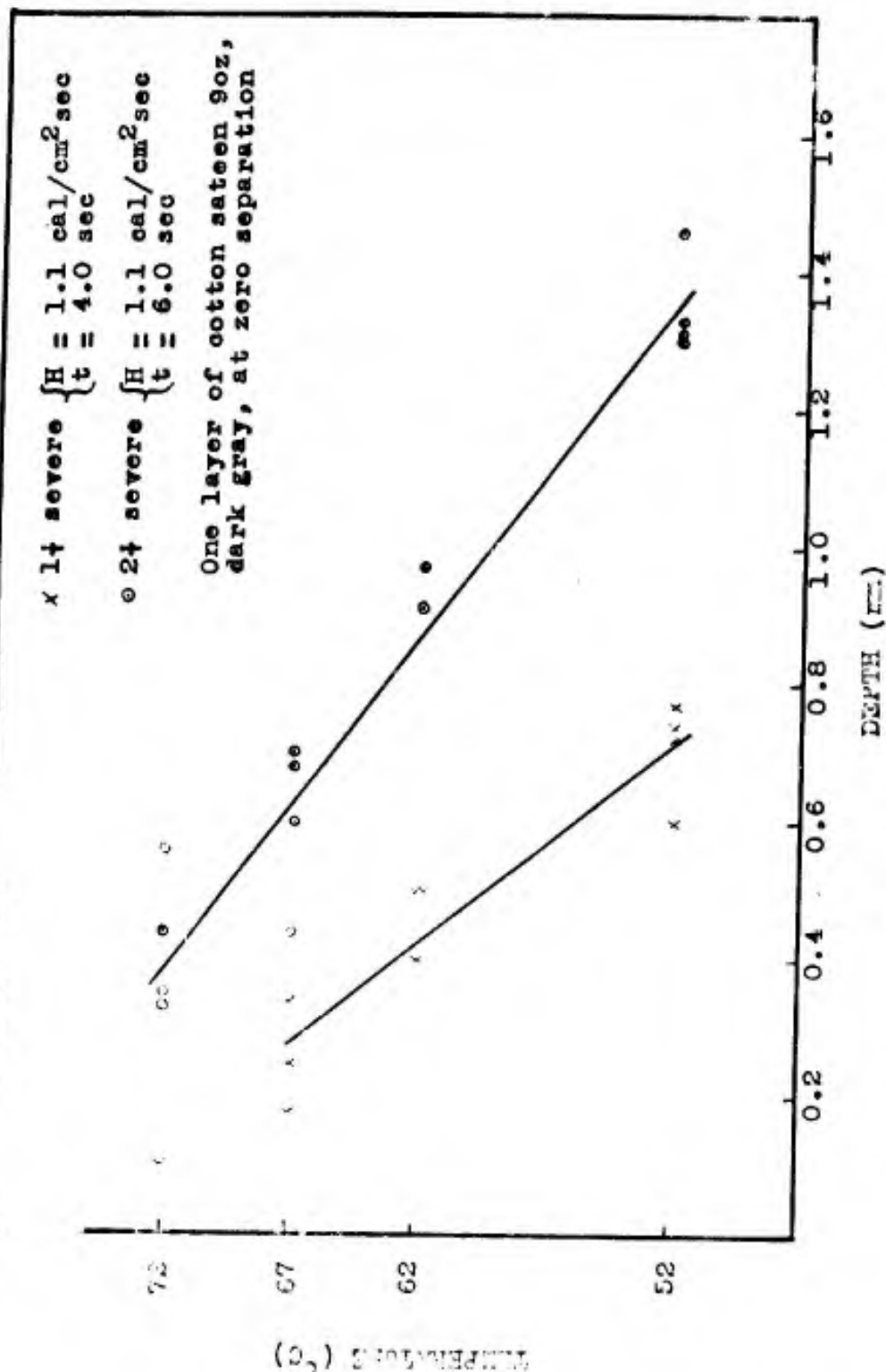
One layer of cotton sateen 9oz, dark gray, at zero separation
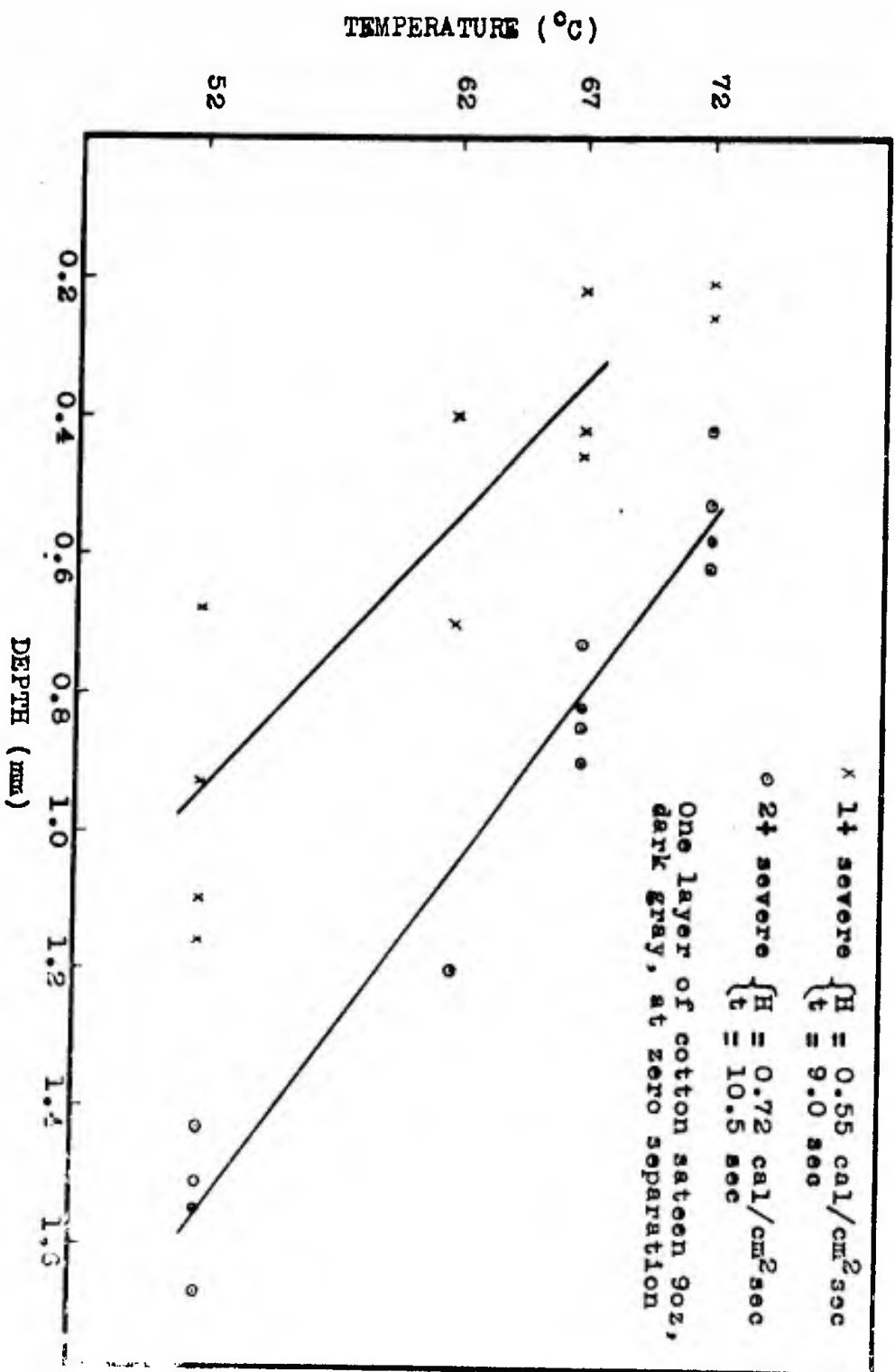
FIG. 18 - Maximum Temperature as a Function of Depth in Polyethylene as Determined by Four Temperature Sensitive Papers
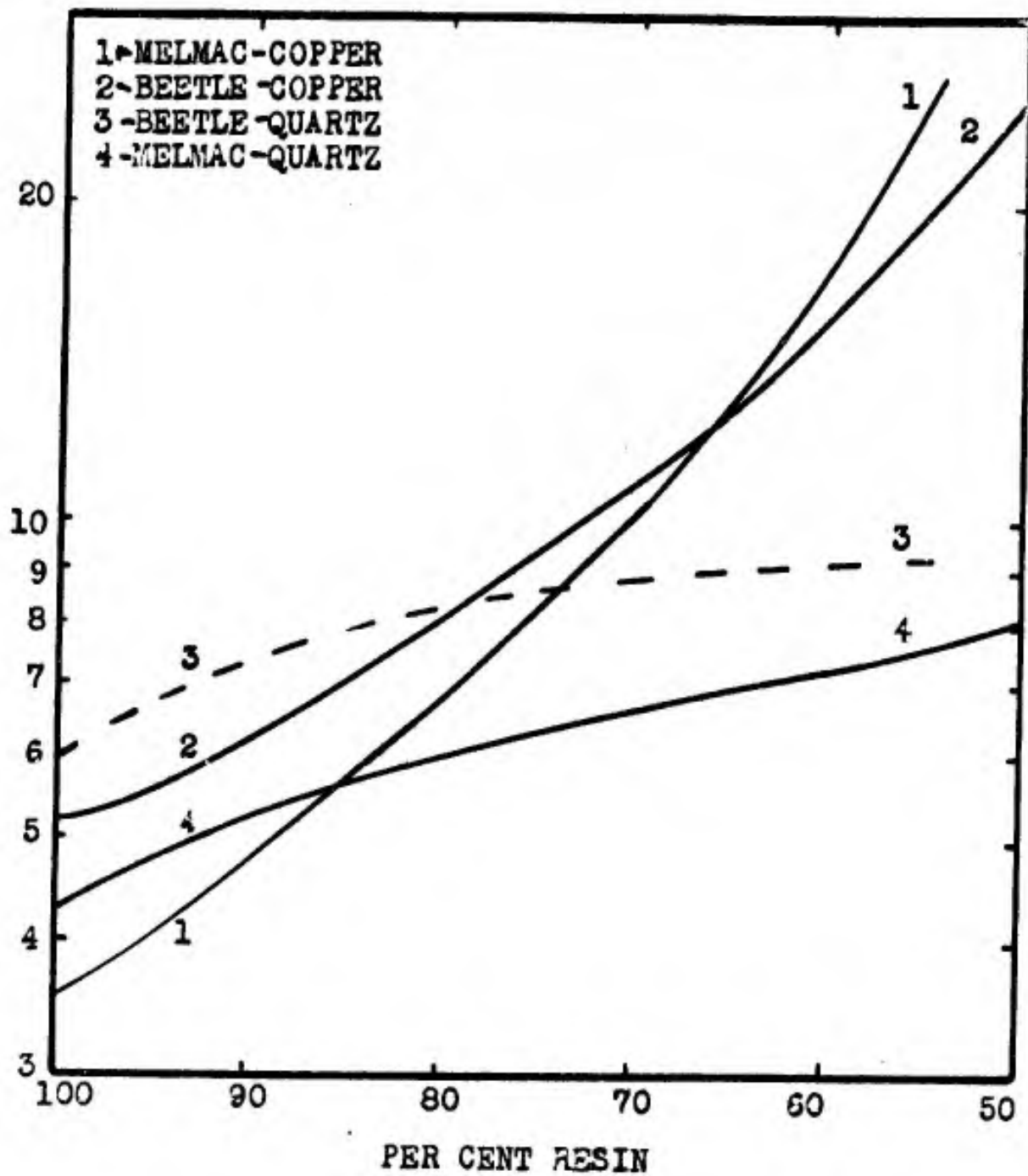
Fig. 19 - Ideal Skin Simulant kρc of Resin-Metal and Resin-Quartz Mixes

Material Laboratory

Lab. Project 5046-3, Part 84
Final Report

TABLE 1

FLASH BURNS TO CLOTH-COVERED PORCINE SKIN-CORRELATION OF RADIANT EXPOSURES DETERMINED EXPERIMENTALLY WITH THOSE PREDICTED BY THE TEMPERATURE RISE OF THE COATED POLYETHYLENE SKIN SIMULANT

Shade of 9 oz. Cotton Sateen	Cloth-Backing Separation (mm)	Irradiance (cal/cm²sec)	Critical Radiant Exposure (cal/cm²) NML	UR	Difference(%)
Dark Gray	0	11.5	5.0	3.8	+32
Dark Gray	5	11.5	15.3	15.0	+ 2
Dark Gray	0	0.9	5.5	5.5	0
Dark Gray	5	0.9	14.2	12.4	+15
Medium Gray	0	11.5	6.3	5.6	+12
Medium Gray	5	11.5	17.9	17.0	+ 5
Medium Gray	0	0.9	7.5	6.4	+17
Medium Gray	5	0.9	17.0	16.3	+ 4
Light Gray	0	11.5	9.1	7.3	+25
Light Gray	5	11.5	18.0	19.0	- 5
Light Gray	0	0.9	9.3	9.2	- 1
White	0	11.5	12.2	14.5	-16
White	5	11.5	41.0	34	+20

Notes:
1. NML values based on methods outlined in NML Report 5046-3, Part 42
2. UR values based on values given in private correspondence

TABLE 2
COMPOSITION AND PROPERTIES OF
MOLDED FILLED PLASTICS HAVING A kc OF 8-9x10^{-4}

BASE MOLDING MATERIAL		FILLER		DENSITY	SPECIFIC	k/c	
MATERIAL	%	MATERIAL	%	g/cm^3	HEAT	x10^{-4}	c
Beetle	75	Copper Dust	25	1.96	0.32	22.8	0.63
Melmac (404)	75	Copper Dust	25	1.92	0.32	22.0	0.62
Beetle	75	Quartz Dust	25	1.60	0.36	25.3	0.58
Melmac (404)	50	Quartz Dust	50	1.84	0.32	23.4	0.59
Bakelite	100	(Note 1)	-	1.93	0.39	16.2	0.75

Notes:

1. Special molding cycle

2. Density was determined by actual measurement

3. Specific heat computed, using theory of ideal mixtures

4. Calculated from $kc/(c)^2$

5. "Beetle" is the trade name for American Cyanimid's alpha cellulose-filled urea formaldehyde (C-509,tan)

6. "Melmac" is the trade name for American Cyanimid's melamine formaldehyde

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development of a coating to use with black poly
ethylene to approximate the constants of skin and
use of this simulant to predict burns in porcine
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1   Flash burns
    Physiological
    effects
2   Skin Effects of
    radiation
3   Skin Simulation
I   Monahan, T I
II Derksen, W L
III NS 081 001
IV AFSWP 850

Naval Material Laboratory   New York Naval
Shipyard   5046 3 Part 84

A REVIEW OF THE DEVELOPMENT OF A PLASTIC PHYSICAL
SKIN SIMULANT FOR EVALUATING SUB FABRIC FLASH BURNS
by T I Monahan and W L Derksen   Final Report
22 July 1955   14 p Figs tables (AFSWP 850)

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Progress in the development of a physical skin
simulant to evaluate sub fabric burns is reviewed
including measurement of the optical and thermal
constants of skin in order to compute the skin
temperatures associated with burns and to direct
the development of the ideal plastic skin simulant
development of a coating to use with black poly
ethylene to approximate the constants of skin and
use of this simulant to predict burns in porcine
skin study of the feasibility of using passive
indicators with physical skin simulants

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